ROUGH DRAFT

A FACILITY CONCEPT FOR VALID TESTING AT
TRANSONIC SPEEDS

By

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SUMMARY

The critical need for high Reynolds experimental capability at transonic speeds has been broadly recognized, for there have been demonstrated significant transonic scale effects on wing-shock position and attendant effects on drag-rise Mach number, buffet boundary, and pitching moment characteristics. Of the various transonic facilities considered for provision of high Reynolds number capability, the conventional wind tunnel operated in a semi-continuous mode and utilizing an energy storage system is considered to have the greatest potential. Specifically, a hydro pumped-storage system is proposed to provide hydraulic energy on an intermittent basis at the rate of 500,000 horsepower to propel hydraulic turbines direct coupled to the wind tunnel fans. Pumping to replenish the reservoir will require continuous power estimated at 5 to 10 percent of the maximum drive power. Volume requirements for a thousand-foot head reservoir are minimal and can easily be met by natural sites or man-made excavation.

Utilization of a simple hydraulic-turbine drive should provide substantial initial cost savings as well as a reduction in operating costs associated with the high utilization rates and low power demands of the pumping system. The potential advantages of a multi-research facility site are evident, and consideration of a hydro pumped-storage system as a common energy source for a new research center is suggested.

Part I   Background Information

The continuing development of large transport aircraft cruising
near the speed of sound, and the ~~demands~~ requirements of military aircraft for high
performance at transonic speeds, has resulted in new demands upon available
ground-based wind tunnel facilities. (Reference __ Heppe). These demands
entail not only tests at higher Reynolds numbers but also the requirement for,
greater precision of data such that valid extrapolations to full-scale
flight conditions can be made. Flight tests on the C-141 (reference __)
and Blackwell in reference ___ demonstrated at high subsonic speeds the
existence of a critical shock boundary-layer interaction problem as illustrated
in figure 1 . Under low Reynolds number test conditions the upper surface
shock position is shown to ~~move~~ be forward with an attendant increase in the
separated region behind the shock. As the test Reynolds number is increased,
the shock moves rearward with an attendant reduction in the area of
separation and a rearward shift in center of pressure. The experiments of
reference __ demonstrated that the shock location is critically dependent
upon the test Reynolds number and is determined largely by the ratio of
boundary layer displacement thickness in the region of the shock relative to
the length of the airfoil chord.

The manifestations of a change in airfoil shock location are
significant and fundamental to the prediction of aircraft performance at
transonic speeds. As shown in figure 2 the level of test Reynolds number
characteristic of current facility capability leads to prediction of
premature drag rise, pitching moment nonlinearity, and low lift coefficient
for buffet onset. Although specialized experimental techniques for two-
dimensional airfoil testing have been developed for simulating full-scale
conditions (reference __), the applicability is limited and the techniques

become questionable for complete three-dimensional configurations. This is
the basic technical concern that has led to generation of the current U. S.
flight test programs with manned aircraft as represented by the modified
Vought F-8U and North American T-2C aircraft, and by the unmanned flight
programs discussed by Mr. Gillis in Paper _____ at this meeting (reference __).

The fundamental unanswered question is how much Reynolds number is
required for valid transonic testing. Does the shock position continue to
move aft with increasing Reynolds number or does it essentially stabilize
at some rearward position. Igoe and Baals in Paper 5 (reference__) presented
at this meeting have found an apparent plateau of shock position versus Reynolds
number to exist. Figure 3 is a summary plot of these results. The ordinate
represents the increment in shock travel expressed as a fraction of the total
travel increment for a Reynolds number range from 1 to 100 X 10^6 based on
mean chord. Consistent wind tunnel and flight data are shown for the T-33
and C-141 aircraft at transonic speeds. Although the available data are
still too limited to generalize, the trend of the results suggests the
requirement for test Reynolds number capability of approximately 30 to 50 X 10^6.

Figure 3 also depicts the change in turbulent skin friction for
a Reynolds number range from 1 to 100 X 10^6 expressed as a fraction of the
total skin friction change. Testing capability of 40 million Reynolds
number, for example, would represent full-scale conditions for most fighter
conditions and provide 90 percent of the skin friction change for a Reynolds
number range from 1 to 100 million.

The facility implications for attainment of transonic test Reynolds
numbers of approximately 40 million based on mean chord are rather sobering.
The largest transonic wind tunnel in the United States — the AEDC

16-Foot Transonic Propulsion Tunnel — has a drive power of 216,000 horsepower and generates at Mach 1 for an appropriate sized complete aircraft model only about a quarter of the indicated level of Reynolds number required. A full Reynolds number wind tunnel with conventional electric drive would require drive powers upwards of a half million horsepower with a total facility cost of approximately $100 million. Either new facility concepts will be required to reduce the initial costs or greater ingenuity will be required in the engineering design of the conventional approaches.

Part II   Consideration of Facility Types

As pointed out in the recent NASA/USAF ad hoc report on transonic scale effects and test techniques, the ultimate goal of any test facility is to provide valid experimental data such that prediction of full-scale aircraft performance can be made with accuracy and confidence.
Reynolds number is only one facet of the total problem. Equal consideration must be given to test flow quality, wall-boundary corrections, model accuracy, support-system interference, and instrumentation performance. From the standpoint of total data accuracy, little may be gained in attaining high Reynolds number, if in the process there results a degradation in test flow quality, instrumentation performance, or the introduction of an unpredictable aerodynamic interference effect.

There are many types of ground-based facilities to provide practicable high Reynolds test capability. The basic types are as follows:

Ludwieg tube: Run duration is determined by the length of charge tube and tends to be of the order of one second with attendant limitation, in data productivity and instrumentation accuracy. Run time cannot be extended by operation at reduced density levels. Flow quality should be high. The facility concept probably represents the most economical approach to high Reynolds number and lends itself to basic fluid mechanics research. Operational experience at transonic speeds, however, is limited; noise levels may dictate a remote site.

Intermittent Blowdown Facility: This is a basic facility type. Economics of design usually dictate run times of the order of one minute. There is an inherent design problem associated with quality of flow resulting from upstream pressure regulation, flow turbulence, and changing total temperature. In contrast to the Ludwieg tube, run time can be increased by testing at lower pressure levels with an attendant increase in productivity of data. Operating noise levels are high.

Semi-continuous wind tunnel: This facility concept implies a limited run duration (e.g., 15 to 30 min.) associated with utilization of some form of energy storage system. Such a facility has the inherent capabilities of the continuous flow facility limited only by the restraints of finite run time. The productivity of modern data acquisition systems, however, can effectively eliminate the latter restraints. The great potential of the semi-continuous facility lies in the areas of reduced costs of the drive system and its operation, and in the capability for full-power operation without external system restraints.

Continuous-flow wind tunnel: Run time can be in hours. Productivity is high, for data acquisition productivity is directly associated with the

available run time. This factor, combined with the benefits of stabilized

conditions, good flow quality, etc., makes this type of facility preeminent

throughout the world. Propulsion by conventional electric drive motors is

costly, however, and for large powers may seriously impact *electrical* network capability

and necessitate maximum power operation during "off-peak" hours only.

Ground track facility: Transonic speeds for tracked vehicles is

technically possible, but the potential appears limited for productive tests

of high data precision. Problems of atmospheric variations, support

interference, and ground reflections remain largely unresolved for practicable

facility schemes. Costs per data point are high. The greatest potential

for such a facility would appear to be for very limited and specialized

testing.

Part III Semi-continuous Wind Tunnel With Energy-storage System
A. *Technical consideration leading to selection :*

An analyses of the foregoing facility considerations has led our

team at Langley to select the semi-continuous flow wind tunnel, with its

potential for overall flow quality and anticipated economy of operation, as

the most likely candidate facility for high Reynolds number transonic

research. From a research standpoint the basic characteristics of the

continuous-flow type facilities — whether they have infinite or finite

run time capability — may be summarized as follows:

Flow quality: The conventional return-type wind tunnel with

careful design can obtain the highest quality of flow in the test section

from the standpoint of pressure, temperature, and humidity control; low

turbulence level; precision of speed control; and uniformity of flow in

the test section.

Accuracy of data acquisition: The capability of measuring data under steady state conditions (such as "pitch and pause" mode) provides a potential for unequaled accuracy of data acquisition. The opportunity to "time average" data where required or to determine accurately the model/sting deflections under load are factors which contribute fundamentally to total data reliability.

Flexibility of experiment: The greatest experimental potential is the availability of run duration to accomplish finite time experiments or to establish equilibrium conditions for such tests as:-

- Visualization of surface flows by liquid film and sublimation techniques.

- Stabilization of operating model propulsion systems for propulsion integration tests.

- Study of aeroelastic problems associated with flutter, buffet, and related phenomena.

- Store separation investigations where the store is computer programmed to the next point on the trajectory.

Data productivity: This is a direct function of run duration, instrumentation response, and model support and actuation systems. If adequate data accuracy can be obtained by a pre-programmed dynamic sweep of angle of attack as required in short duration intermittent facilities, for example, then this technique can and should be practiced in continuous operation facilities as well. In the area of data productivity the potential of the continuous-flow type facility remains unequaled.

B. Potential for cost-reduction via semi-continuous operation

1. Propulsion system costs: Consideration of the aforementioned technical advantages of the continuous-flow type facilities attests to their recognized research superiority and world wide acceptance. However, as the facility size and drive power are increased to meet the dictates of high Reynolds number capability, a facility design concept based on continuous operation capability becomes questionable because of the projected high facility construction and operating costs. The propulsion system is the heart of the problem, for this element alone can represent upwards of 50 percent of the total facility costs. Conventional electric drive systems range from $50 to $100 per horsepower dependant upon the speed control range and quality of regulation. A commercial gas-turbine drive tends to fall in this cost range also.

2. Utilization factor: The objective of our initial facility planning was the retention of the basic capabilities of a continuous operating facility but incorporating the potential economies associated with some form of an energy storage system. The first step in such an undertaking was an assessment of the operational utilization of the major Langley wind tunnels to provide an indication of required energy makeup rates. The facilities considered were the 16-Foot Transonic Tunnel, the 8-Foot Transonic Pressure Tunnel, and the Unitary Plan Wind Tunnel. These research facilities operate on a 16-hour day, 5 days per week with energy utilization similar to that shown on Figure 4.   The ratio of the actual energy used (shaded area) to the maximum *demand energy* (peak power X 16 hours) is termed the utilization factor in percent. The factor for the subject research facilities ranged from 2.7 percent to 7.3 percent. Production

facilities, in contrast to research facilities would probably achieve a somewhat higher energy utilization factor, but the Langley experience is considered typical of well-operated research facilities.

     3. Energy makeup rates: The significance of the energy utilization factor to the design of an energy storage system is obvious. Assuming an infinite energy storage capacity, a 7-percent utilization factor, for example, would require energy makeup capacity of only 7 percent of the maximum drive power (neglecting inefficiencies). If the tunnel were to operate on a typical two shift basis (16 hours) but reenergize the storage system on a 24-hour basis, then the energy makeup capacity need be only 4-2/3 percent of the maximum drive power. For a 500,000 horsepower drive, for example, the energy makeup system for the latter case, assuming a 70 percent conversion efficiency, would only be 33,000 horsepower — a rather nominal value for the maximum power considered.

     Note that these projected rates of energy makeup provide the same level of facility utilization on a semi-continuous basis as are now experienced by our currently operational continuous-flow facilities. A factor that could further reduce the facility operational demands is the capability of advanced data acquisition systems to compress the amount of data gathered in a given time period. Many of the operational techniques developed for intermittent operating facilities (typical one-minute duration) can be applied effectively to longer duration facilities for compressing the data acquisition time. Such techniques as pre-programmed computer-driven stings combined with high response-rate instrumentation can be employed effectively in many experimental programs without sacrifice in the basic data accuracy inherent in a continuous-flow facility. Analysis at Langley indicates the potential for a five-fold

compression in data acquisition times by the employment of advanced technology data acquisition systems. From a facility design standpoint, however, this instrumentation potential for reducing run time cannot be counted on too heavily, for historically the experimenter tends to use this capability in expanding his data requirements.

The preceding analysis of the feasibility of semi-continuous facility operation represents a rather simplistic approach, for the problems associated with finite storage system capacity, start/stop cycle times, and overall system efficiency are pertinent to such an assessment. Yet the analysis clearly demonstrates from a wind tunnel operational standpoint that a semi-continuous facility operation is feasible without necessarily incurring reduced data productivity. Further, typical continuous-flow facility operation results in such a low energy utilization factor that there is great potential for a facility design incorporating an energy storage system with the potential for reduced initial and operating costs.

Part IV   Energy Storage Systems

An energy storage system for the wind tunnel facility under consideration must be applicable to energy release at the rate of approximately 500,000 horsepower or more for a duration of 15 to 30 minutes. Under such general requirements only two basic systems appear practicable for further consideration. The first is stored air at pressure and the second is water at elevation.

Pressurized air storage systems:

The major problems of air storage systems are the high costs of the pressure vessels and pumps as well as the low overall efficiency of the system. Air stores most efficiently at high pressure and low volume,

whereas transonic tunnel operation requires large volume, low pressure ratio flows. (This is in contrast to supersonic/hypersonic facility operation). The disadvantages of a direct blow-down facility in terms of flow quality have been noted in previous sections. The use of high pressure ejectors to induce large volume flows is grossly inefficient and does not merit further consideration here.

Other ingenious schemes have been proposed which utilize stored high-pressure air to drive air turbines direct connected to a cluster of commercially available jet-engine fans. This approach would appear to have application to more modest powered transonic facilities having relatively limited run time. A variant of this concept employs the use of an underground air-storage cavern under a hydraulic head to provide an intermittent but constant-pressure air supply. The pressurized air is then heated in combustors and expanded through a low-speed gas turbine direct coupled to a single-stage wind tunnel fan. This specific concept entails solution to several difficult technical problems and further studies as to the overall system feasibility are being undertaken by the NASA.

Hydro-pumped storage system:

The results of the preliminary feasibility studies completed to date indicate a great potential for a hydro-pumped storage system where the potential energy of water at high elevation is converted to mechanical power by means of hydraulic turbines direct coupled to the wind tunnel fans. Reservoir size and pump recharging rate would be determined by facility utilization schedules. Such a concept is now under technical feasibility study by hydraulic engineering specialists under contract to NASA Langley. Although it is premature to assess the findings of this study, the

background technical considerations upon which the study were premised should be enlightening.

Energy storage potential.- The potential energy of water at high head is truly fantastic. For example (see figure 5) a sphere of water 200 feet in diameter at 1000 foot head will drive a 500,000 horsepower turbine for approximately 15 minutes. Costs of construction of such a water tower appear prohibitive, but as will be shown later, an earthen reservoir constructed on top of a natural elevation represents an economical approach. Of course, a high-head site with a natural supply of water as represented by the ONERA/Modane installation, in the French Alps is a classic example of wedding a natural site and its water flow to the facility requirements. A survey for a similar site has not been attempted in the United States as yet, but it will undoubtedly become a high priority item as the proposed facility concept continues to progress.

Direct fan drive by hydraulic turbines.- Probably the single most important advantage of a hydraulic energy storage system is the capability of using hydraulic turbines directly coupled to the wind tunnel fan. The rotational speeds of large hydraulic turbines are characteristically low, and fortuititiously this can be made to match the wind-tunnel fan rotation requirements without the necessity for gearing. Elimination of the latter requirement is a major step forward in mechanical simplicity and costs.

Hydraulic turbines have demonstrated excellent speed regulation characteristics at or near the design RPM. Precise speed regulation through a wide percent RPM and power range has been demonstrated only for the impulse type machines (Pelton wheel) of high head and moderate power (e.g., Modane installation). Although the potential exists, such characteristics have

yet to be demonstrated for the reaction units (Francis turbine) of moderate head and high power. General studies are now underway to define the characteristics of high-power hydraulic turbines as applied to wind tunnel drives considering variants in the basic systems as well as combinations thereof.

Component efficiency and costs.- The efficiency of the hydraulic components in a hydro-pumped storage system is high and can be upwards of 90 percent for efficiently designed large reaction turbines and pump. With reasonably short penstock runs, the overall efficiency of a pumped-storage hydraulic drive system, defined as the ratio of turbine drive-shaft output to the reservoir pumping system input is approximately 70 percent.

The costs of the large turbine drive units which are the heart of the hydraulic propulsion system are surprisingly low. For example, current uninstalled costs for a reaction turbine of 250,000 horsepower are estimated at $6 per horsepower including speed regulating equipment and cut-off valve. Thus, if a hydraulic drive system can be designed to minimize installation costs, there is the potential for a new low level of costs for the wind tunnel drive system.

Basic technology available.- The electrical industry in Europe and the United States has pioneered the concept of pumped-storage hydro-electric plants for storing energy to level off electrical system demands. During "off peak" hours an electrical motor-pump unit pumps water to an adjacent high-altitude reservoir. During "on-peak" hours the cycle is reversed and the water flows back through the unit (now serving as a turbine-generator) to generate "on-peak" electrical power.

The Taum Sauk plant near St. Louis, Missouri (see figure 6) was placed in operation in 1963 and is illustrative of the intermediate-

sized pumped-storage plants. The two pump-turbines are rated at 250,000 horsepower each at 200 RPM and operate at an average head of 800 feet. Total plant output is 350,000 KW. The upper reservoir has a capacity of 4350 acre feet and was quarried into the top of a nearby granite hill and then asphalt lined. The upper reservoir connects to the turbines by a 7000-feet long underground tunnel partially steel lined. It should be pointed out that relative to reservoir size, a design wind tunnel run of 500,000 HP for 15 minutes would require only about 100 acre feet. Thus, although the turbine drive power matches the wind tunnel requirement in this example, the reservoir size could be reduced by a factor of 10 or more.

The basic technology represented by the Taum Sauk plant is being expanded in new facilities around the world. In Virginia, for example, a 1,500,000 KW pumped-storage facility in the final planning stage is located only a few hundred miles from Langley. The momentum generated by these new projects will lead to a technical fallout which will have direct application to the problems of high-powered wind tunnel drives.

Auxiliary advantages.- The availability of large quantities of water at high pressures opens up many opportunities for advantageous utilization of this potential. Hydraulic power can be used for such auxiliary pumping requirements as test section plenum suction, which may be as much as one-half the drive power at transonic speeds, and for tunnel pressurization and evacuation systems. Use of available water for cooling of the wind tunnel is an obvious use. The heat equivalent of a half-million horse-power in cooling towers is a sizable load and represents a substantial investment which can be eliminated. The required water flow for tunnel cooling need only be about five percent of the main flow requirements.

It might also be noted at this point that the ^reservoir energy pumping rate can be a modest 5 to 10 percent of the main drive power. If the site location should so dictate, the facility could be cut off completely from the need for any external electrical power source. For example, reservoir pumping could be accomplished by gas turbines or by coal or gas-fired steam-driven pumps. Constant frequency electrical base load or variable frequency experimental loads could be provided by hydraulic driven electrical generators. Certainly such broad power flexibility opens up a wide range of site selections and power schemes.

Facility constraints.- The concept of a wind-tunnel facility utilizing a hydro pumped-storage scheme carries with it certain basic facility design limitations. First, a new site must be developed that provides a reservoir system of the required elevation and an attractive location for the facility complex. Since the selected site probably cannot be located at an operational research center, then it must be made completely self sufficient in provision of the many facility support services and skills. Further, the reservoir, penstock, and tailrace systems are a major cost item and sensitive to many site and facility related factors; thus, the engineering design becomes a complex and interrelated problem. Relative to the design and operation of the large hydraulic turbines under consideration, there remain substantial questions as to the overall feasibility for wind tunnel drives considering such factors as RPM range available, regulation under partial speed/power operation, horizontal shaft rotation, and similar hydraulic design considerations. Studies in these areas must progress parallel with the facility and site designs to establish the overall feasibility of the proposed high Reynolds number transonic facility. The engineering studies to

date offer every encouragement that the great potential of the hydraulic wind tunnel drive system can be realized in the large powers envisioned.

Part V   Proposed Facility Characteristics

The previous sections of this paper have considered   various facility types   for high Reynolds number transonic testing and the selection of an efficient facility propulsion system. In the succeeding sections the selection and sizing of a semi-continuous flow wind tunnel will be developed to meet currently estimated transonic Reynolds number requirements. Since the latter requirements are in a very preliminary state, the facility proposed herein must be considered as a baseline configuration which would be subject to revision as the transonic Reynolds number requirements and hydraulic propulsion system constraints are better identified.

A.   Basic facility requirements.- On the basis of transonic facility experience and the results of the transonic Reynolds number study discussed previously, the following basic facility requirements are assumed:

Mach range	0.2 to 1.4
RN at Mach 1	40×10^6 based on $\bar{c}$
Max. dynamic pressure	4000 psf
Design run schedule	30 min. at 1/2 power every 4 hours.

General justification for these assumed characteristics has been considered previously except for maximum dynamic pressure. Since from a facility standpoint it is most efficient to attain Reynolds number by pressure rather than facility size, the "q" limit should be set as high as practicable. The "q" limit of 4000 psf was established on the basis of model, balance, and sting deflection and stress considerations. This limit is a key factor, and further study will be required before a final decision can be made.

B. Model size relative to test section.- Model and test-section size relationships for valid testing at near-sonic speeds are critical. The purpose for which the tests are being run becomes the controlling element, but, in general, the following criteria based on Langley experience must be met for testing at high subsonic speeds ($M \rightarrow 1$) in a slotted-or porous-wall test section:

1. The ratio of model cross-section area (A_{max}) to test section area should be less than 0.005 from considerations of tunnel choking.

2. From the standpoint of lift interference, the ratio of model span to test-section width is the critical parameter. For high aspect-ratio configurations ($AR \approx 7$) a span ratio less than 0.7 is employed; for lower aspect ratio configurations ($AR \approx 3$), the value should be less than 0.5.

3. For valid testing at supersonic speeds, the model must be free of wall-reflected shocks. A usual transonic criteria is shock reflection free at $M = 1.2$.

In figure __7__ four basic aircraft types are investigated relative
to the model sizing criteria. Aircraft have been selected to represent a
typical subsonic transport, near-sonic transport, a supersonic transport,
and a fighter aircraft. Three columns of key parametric data have been
assembled:

A_{max}/S : ratio of max. cross-section area to wing area

$\bar{c}/b$: ratio of mean chord to wing span

$\bar{c}/\ell$: ratio of mean chord to fuselage length

Assuming a test-section size of 10 by 10 units, the three model sizing criteria
of tunnel choking, lift interference, and wall reflection have been utilized
separately to determine model size. It will be noted that the illustrative
fighter-type configuration (low aspect ratio and low fineness ratio) enjoys
the largest mean chord, whereas the remaining configurations are constrained
to some lower chord value largely because of overall length.

      C. <u>Derived facility characteristics</u>.- Based on an analysis
similar to the preceding section, a ratio of model chord to test section
width of 0.1 has been selected for the purpose of preliminary determination
of test section size. Figure 8 depicts at Mach 1 the variation of test
section dynamic pressure, q, and Reynolds number per foot as a function
of the tunnel stagnation pressure (expressed in atmospheres). Based on this
figure, the following wind tunnel characteristics are derived for a "q_{max}"
of 4000 psf.

Stagnation pressure	5 atmospheres
Max RN/ft	20×10^6
Mean chord for RN $= 40 \times 10^6$	2 foot
Test section size	20 X 20 ft*

*(20 ft. = 6.10 meters)

D. <u>Facility power requirements</u>.- The tunnel characteristics
are now sufficiently determined to establish the facility power
requirements. For estimation purposes the power data from several of the
major transonic wind tunnels were assembled on a common basis. In figure <u>9</u>
is plotted as a function of test-section Mach number the shaft horsepower
per square foot of test-section area for one atmosphere stagnation pressure.
The open symbols represent drive motor power; the solid symbols represent
total power including the plenum chamber auxiliary suction. Two Langley
facilities, the 16-Foot Transonic Tunnel and the 8-Foot Transonic Pressure
Tunnel demonstrate values of 225 and 250 HP/ft.^{2} respectively. On the
at Mach 1
assumed basis of 250 HP/ft^2 (1 atm), the facility drive power becomes
500,000 horsepower to provide an average test Reynolds number of 40×10^6
at Mach 1. Power requirements at the supersonic Mach numbers are indeterminate,
because for the present no critical Reynolds number problems are definable
once the wing leading and trailing edge shocks are attached. Thus, the
tunnel density at supersonic speeds can be reduced to a level where the Mach 1
power requirements dictate the design power.

E. _Facility characteristics_.- The facility aerodynamic character-
istics and horsepower requirements are summarized in figure |O . The heavy *dashed*
line depicts the maximum drive power available as a function of test section
Mach number. For the sake of simplicity the lines depicting tunnel power
requirements above Mach 1 are drawn to include main drive plus the auxiliary
power associated with the test section suction requirements. Nevertheless,
the point can be made that drive power is available below Mach 1 to increase
the stagnation pressure and improve the subsonic Raynolds number capability.
The tunnel shell design will be the limiting factor here, with 10 atmospheres
set as a tentative design limit. Above Mach 1, the tunnel density level
(and attendant Reynolds number) will have to be reduced to meet the
available drive power limits.

F. _Facility layout_.- The general facility (figure||) layout is
conventional in every respect. Tunnel power will be supplied by two
hydraulic turbines driving fixed-pitch counter-rotating fans. The turbine
drive configuration and the attendant tunnel lines are now under study.
Cooling coils will be located in the settling chamber followed by a turbulence
damping screen system. The walls of the test section will be ventilated for
optimum transonic flow characteristics. The particular wall configuration
and associated plenum suction requirements have not been determined but
will be the subject of future studies. This is an important design aspect,
for suction powers can be as large as half the main drive power. Test-
section isolation doors will be included along with model-support dollies
for quick model interchange. A high-speed data acquisition system will
provide on-line computing for test monitoring during the run.

Part VI   Design and Operational Considerations of a Hydro Pumped-Storage

System

The design evolution of the hydraulic drive and pumped-storage system concept applicable to a large transonic wind tunnel results in a site layout illustratively depicted in figure 12 . The engineering realities of the hydraulic drive installation may change the facility and site layout in detail but not in concept. The conceptual studies have been extended to include considerations of the pump/reservoir sizing as well as relative operating costs.

As a guide to establishing the relative size of pump and reservoir for various modes of pumping operation for the proposed facility, some simplified operational schedules have been assumed as a basis for analysis. The total hydraulic power has been estimated as 600,000 horsepower of which 100,000 is in tunnel auxiliaries. The assumptions and analysis are outlined in the following paragraphs:

- TUNNEL OPERATIONAL MODES

  - Typical run: 300,000 HP for 30 min. (Full power of 600,000 HP for 15 min.)

  - Run frequency: Once every four hours

  - Shifts: Two 8-hour shifts, 5-day week (20 runs/week)

- PUMPING SCHEDULES

  A. Pump 4 hours per run (Minimum reservoir size)

  B. Pump 24 hours per day, 5 days per week

  C. Pump 24 hours per day, 7 days per week (Week cycle for pump/reservoir with reservoir filled Monday morning)

D. Pump "Off-Peak" hours only. (Off-peak electrical hours
of 8 per week day, 20 hours on Saturday and 24 hours on
Sunday for total of 84 hours/week)

● HYDRAULIC SYSTEM CHARACTERISTICS

- Assume electrically driven turbine pump

- Overall pumping cycle efficiency of 70 percent. (Ratio
of pump KWH input to hydraulic drive turbine KWH output)

- Capable of reservoir pumping while tunnel runs

The pump power and reservoir capacities are summarized in
figure 13.

The corresponding electrical power costs for assumed operational
schedules (A, B, C, and D) for the pumped storage concept are tabulated in
figure 14. The current rates in effect at Langley are as follows:

Demand rate ON PEAK $1.70/KW

OFF PEAK 0.55/KW

Energy rate 4.1 mill/KWH

($0.0041/KWH)

For comparison with the pumped storage concept of operation,
figure 15 presents the electrical power costs for the condition where the
tunnel fan is driven by a 600,000 HP electrical drive motor direct connected
to the local electrical network. For these conditions the following power
demand schedules to provide two-shift operation are considered:

Schedule I	600,000 HP on peak	5 day week
Schedule II	300,000 HP on peak	5 day week
	600,000 HP off peak	
Schedule III	600,000 off peak	7 day week

(assumes 80 hours off-peak including week end)

PRELIMINARY CONCLUSIONS

(a)   Pumping schedule B (24 hours per working day) appears to
be an efficient design basis for the proposed pumped-storage project.

For a 100 percent increase in minimum reservoir capacity,

pump size is reduced by one third to a value of about

6 percent of the rated tunnel drive power.

(Schedule D)

.   (b)   Pumping during "off peak" hours only requires about a
12-fold increase in minimum reservoir size.

Electrical power costs would be reduced by approximately

$300,000 per year compared to Schedule B.   This may not be

a good trade.

(c)   Some form of energy storage system appears mandatory for
large wind tunnel drives.

For the pumped-storage concept annual electrical charges

range from $935,000 to $1,500,000 — dependent on

reservoir/pump size.   Corresponding unit electrical costs

are 5.6 to 9 mill/KWH.   Demand charges range from 0.37

to 1.2 times the energy charge.

(d)   For a large tunnel drive (600,000 HP) direct connected to
the electrical network, there appears to be no economical mode of tunnel
operation under current electrical rate schedules.

Annual electrical charges vary from \$3,640,000 for "off-peak" operation to \$10,230,000 "on-peak". Corresponding unit electrical costs are 29.4 to 82.6 mill/KWH. Demand charges range from 6 to 19 times the energy charge.

It should be noted that the pump size tentatively selected for initial design study (26,667 KW = two 18000 HP units) would permit propulsion by off-the-shelf industrial gas turbines fueled by either oil or natural gas. Such an approach would permit operation without concern for electrical network problems. Gas-turbine as well as steam-driven pumps will be considered in forthcoming studies.

Part VII   Projections

The potential advantages of a hydro pumped-storage system in conjunction with a hydraulic turbine wind-tunnel drive have great merit. The pumped storage concept is simple and the technology is largely in hand. There is always the potential for a site location where a natural supply of water would be available (either total or partial) to supply the basic energy needs. Consideration should also be given to location at the base of a high-head dam site, or adjacent to a large pumped-storage project. The latter approach does not eliminate the need for hydraulic pumping, but the energy storage requirements of the proposed facility are so modest — only about two percent of a 1,500,000 KW system — reservoir sharing becomes feasible.

The greatest potential for a hydraulic drive and energy storage system, however, is found not in a single facility site but in a multi-facility center. Once the investment in a new site has been made in terms of a reservoir, penstock, and pumping system, it becomes feasible to add comparable facility power loads by merely increasing the capacity of the pumping system. Additional facilities of larger power or longer run time, however, would necessitate increases in the reservoir size and penstock system as well. Such considerations should enter into the selection and design of the initial site.

The United States Unitary Plan Act of 1949 resulted in a complex of major aeronautical facilities in the 100,000 to 200,000 horsepower range located at existing NACA/NASA research centers and at a new Arnold Engineering Development Center in Tennessee. The latter location was selected largely on the basis of availability of the electrical power system of the Tennessee Valley Authority. The Unitary Plan Act is now over 20 years old. Technological pressures are mounting for a new round of large, high-powered research and development facilities (reference __) which could dwarf any of those now in existence. In the interest of efficient national planning, consideration should be given to the potential of an integrated multi-facility site incorporating a hydro pumped-storage system with hydraulic turbine propulsion for the individual facilities. Exploitation of such a concept could provide the technical initiative and design basis for a new generation of aeronautical research facilities.

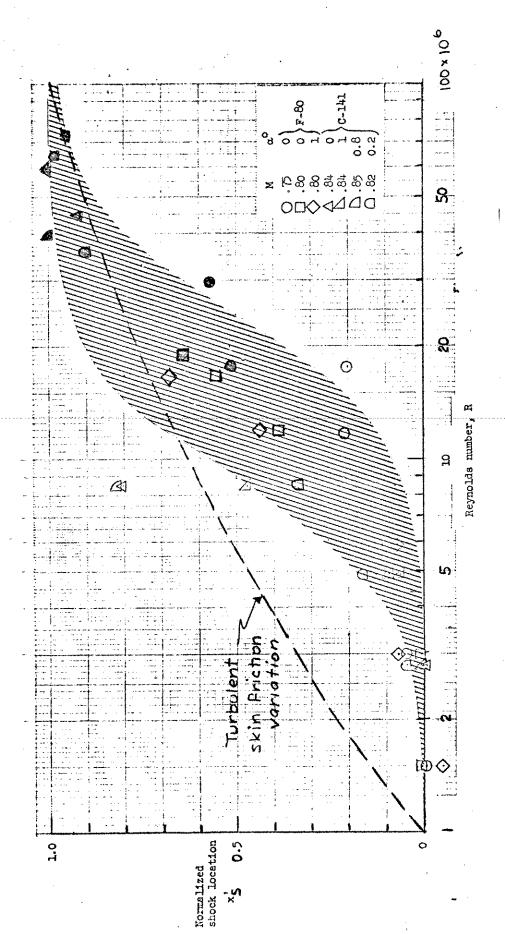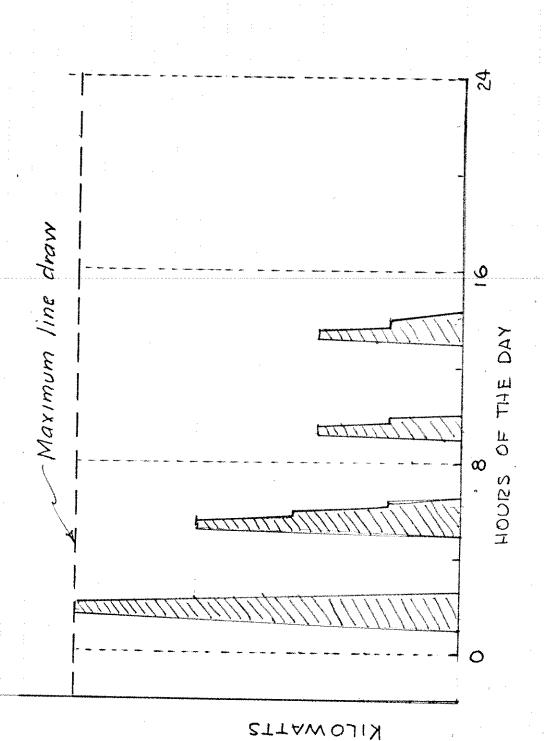Figure 1. – Illustration of shock boundary-layer interaction effects

Figure 2. – Manifestation of changes in c_l, c_d, c_m [illegible]

Figure 3 Variation of normalized shock location with Reynolds number (solid symbols indicate flight data).

Figure 4. – Typical wind-tunnel energy utilization on a two-shift basis.

WATER TOWERS RELATIVE TO 16' TT SIZE

Figure 5. –

TAUM SAUK PUMPED-STORAGE
HYDROELECTRIC DEVELOPMENT
IN THE MISSOURI OZARKS

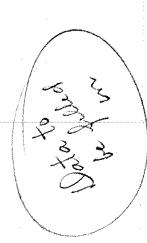| AIRCRAFT	$\frac{A_{max}}{S}$	$\frac{\bar{c}}{b}$	$\frac{\bar{c}}{\ell}$	AR	Chord Criteria, $\bar{c}$/Test section width		
					Amax	Span Ratio	Length Ratio
Boeing 747							
Sonic Transport							
B 2707-300							
Typical Fighter							
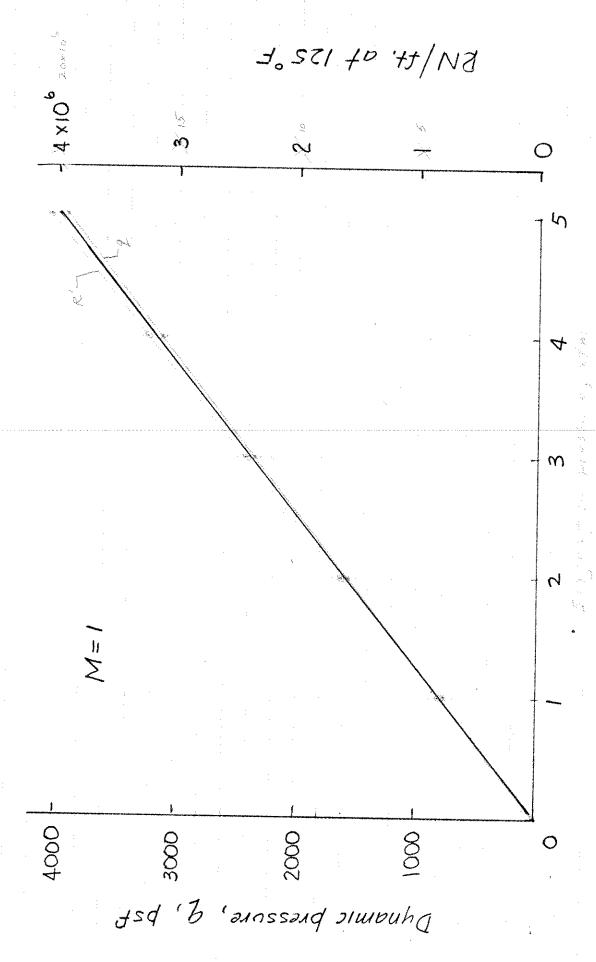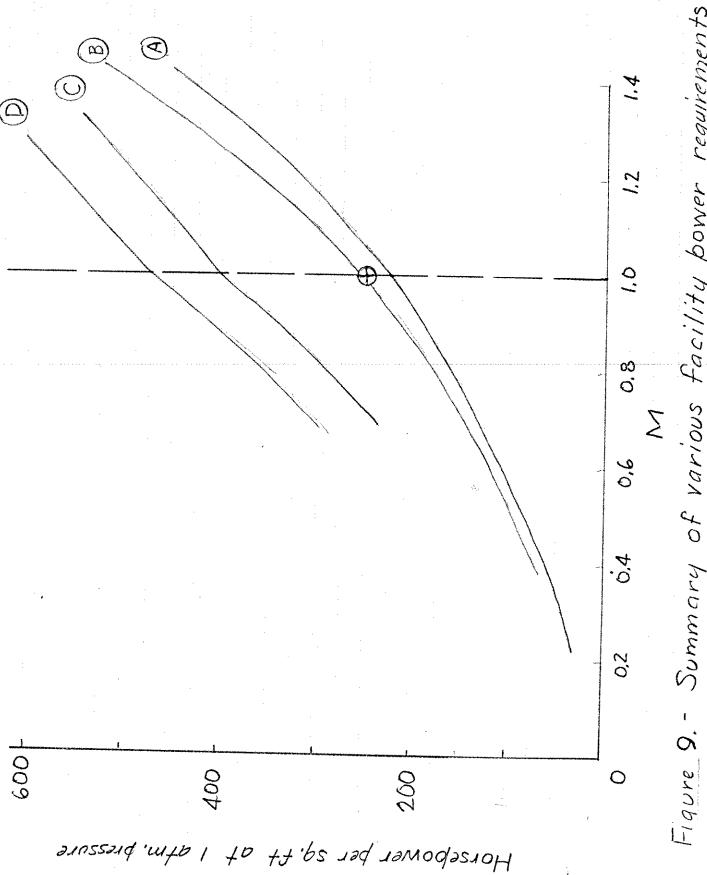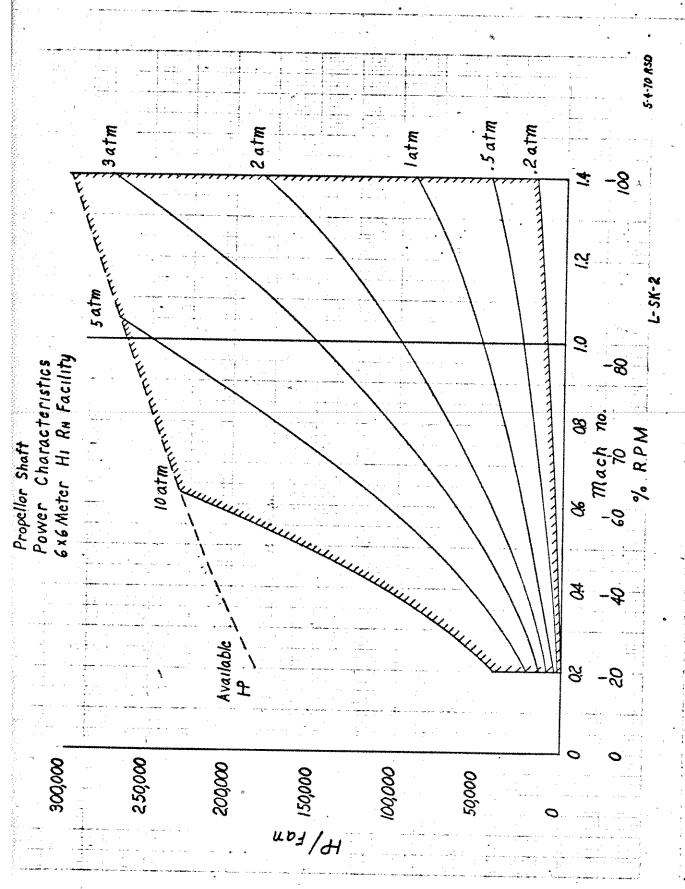
Figure 7. — Model sizing criteria.

Figure 8. — Test section aerodynamic characteristics at M = 1

RN/ft. at 125 °F

Dynamic pressure, q, psf

M = 1

DDB
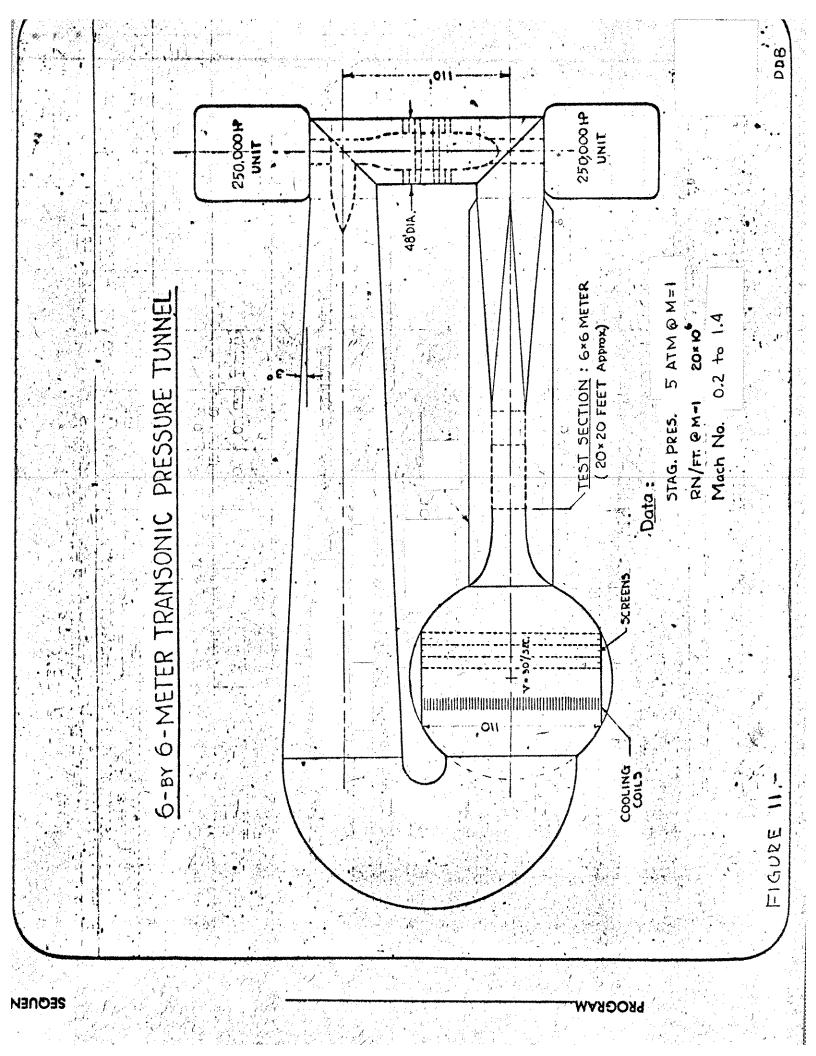
Figure 9. — Summary of various facility power requirements

Figure 10.— Facility power characteristics

6-BY 6-METER TRANSONIC PRESSURE TUNNEL

250,000 HP UNIT

250,000 HP UNIT

48'DIA.

TEST SECTION : 6×6 METER
(20×20 FEET Approx)

SCREENS

COOLING COILS

Data :

STAG. PRES.   5 ATM @ M=1

RN/FT. @ M=1 $20×10^6$

Mach No.   0.2 to 1.4

FIGURE 11.—

Sketch of Single
Facility site.
(Similar to Fig. 16)
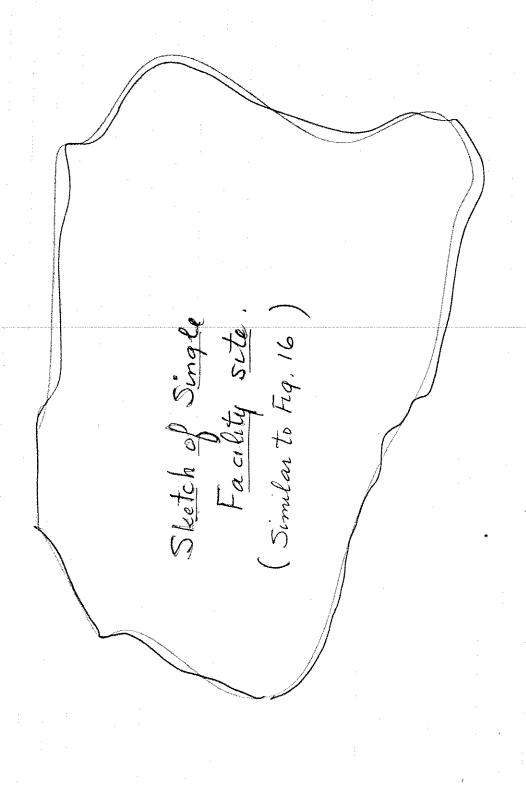
Figure 12. -

FIGURE 13.- COMPARISON OF PUMP SIZE AND RESERVOIR CAPACITY

| PUMPING | PUMP POWER | | RESERVOIR CAPACITY | |
SCHEDULE	KW	RATIO TO (1) DRIVE KW	KWH (2)	RATIO TO Min. Reservoir
A	40,000	8.95 %	160,000	1.0
B	26,660	5.96	320,000	2.0
C	19,050	4.24	1,143,000	7.15
D	38,100	8.52	1,980,000	12.38

(1) Drive shaft HP equivalent = 600,000 HP x 0.746 = 447,000 KW

(2) 160,000 KWH at 800 ft. head requires approx. 195 acre ft.

(acre ft. = 43,560 cu. ft.)

FIGURE 13.-

FIGURE 14.- ELECTRICAL POWER COSTS FOR PUMPED STORAGE OPERATION

PUMPING SCHEDULE	ELECTRICAL CHARGE/Mo. (1)		DEMAND ENERGY	TOTAL CHARGE	
	DEMAND	ENERGY		ANNUAL	mill/KWH
A	$68,000	$57,000	1.2	$1,500,000	9.0
B	45,300	57,000	0.8	1,230,000	7.4
C	32,400	57,000	0.57	1,070,00	6.4
D	21,000	57,000	0.37	935,000	5.6

(1) DEMAND RATE ON PEAK $1.70/KW
OFF PEAK 0.55/KW

ENERGY RATE 4.1 mill/KWH

KWH/Mo. = 13,900,000

FIGURE 14.-

DDB

FIGURE 15. ELECTRICAL POWER COSTS FOR TUNNEL DRIVE DIRECT

CONNECTED TO ELECTRICAL NETWORK.

RUN		ELECTRICAL CHARGE/Mo. (1)		DEMAND		TOTAL CHARGE	
SCHEDULE		DEMAND (2)	ENERGY (3)		ENERGY	ANNUAL	mill/KWH
I	475,000KW "on"	$810,000	$42,000		19.3	$10,230,000	82.6
* II	237,500KW "on"	535,000	42,000		12.7	6,920,000	56.9
	475,000KW "off"						
III	475,000KW "off"	261,000	42,000		6.2	3,640,000	29.4

(1) RATES OF FIGURE 14
(2) MAX LINE DRAW 475,000KW
(3) KWH/Mo. = 10,300,000

* Run Schedule II requires 237,500 KW on-peak demand plus an additional 237,500 KW off-peak demand

FIGURE 15 -

DDB

STORED-ENERGY CONCEPT FOR AN AERONAUTICAL RESEARCH CENTER

FIGURE 16. -